INTC-P-509

Neutron Capture on ^{77}Se, ^{78}Se and ^{68}Zn, and the origin of Se in massive stars

C. Lederer-Woods[1,11], A. St. J. Murphy[1,11], G. Cescutti[2,11], M. Dietz[1], C. Domingo-Pardo[3], R. Garg[1], A. Gawlik[4], K. Göbel [5], R. Hirschi[6,10] , F. Käppeler[7], D. Kurtulgil[5], S.J. Lonsdale[1], N. Nishimura[8,11], J. Perkowski[4], T. Rauscher[9,10,11], R. Reifarth[5], P.J. Woods[1,11], and the n_TOF Collaboration.

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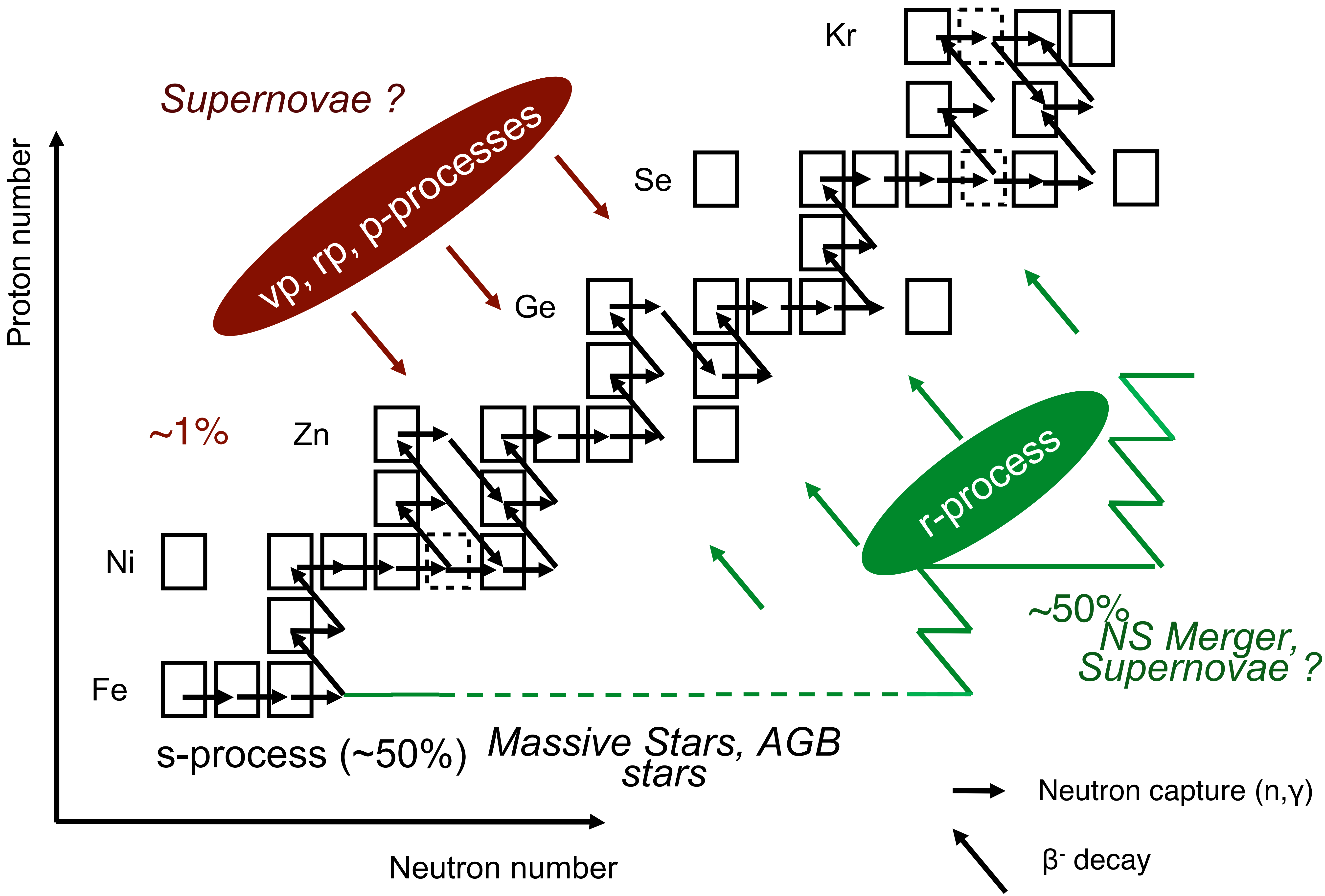
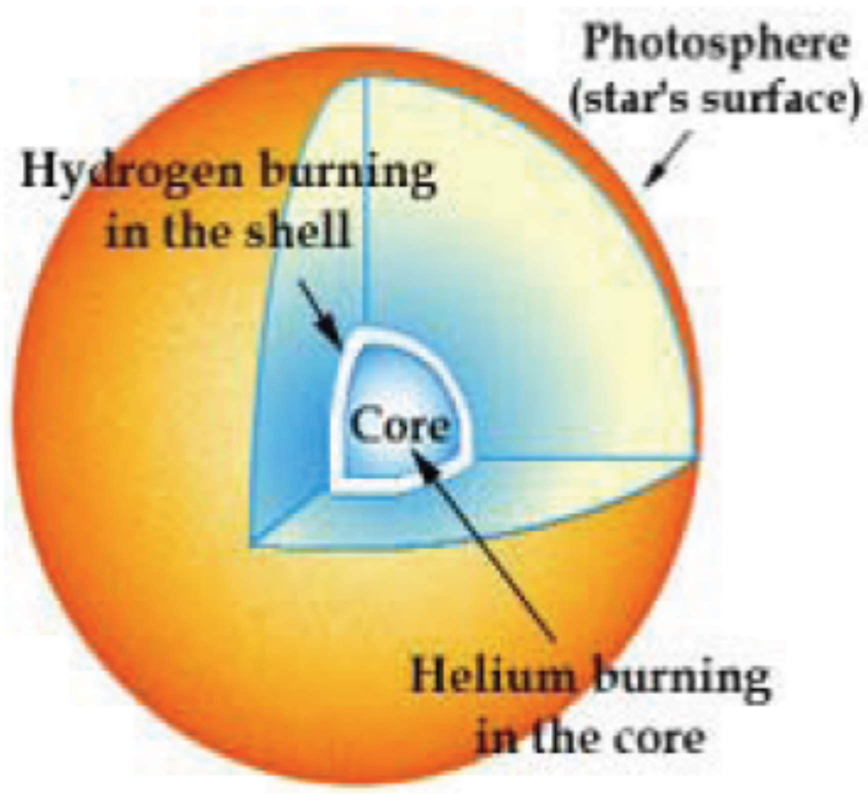
n_TOF

Nucleosynthesis of the heavy elements



s-process in Massive Stars



- **weak s-process** in massive stars (>8 solar masses)
- During He Core burning and C shell burning
- Mainly elements from Fe to Zr
- Stellar temperatures kT~25 keV, and kT~90 keV
- Neutron capture cross sections up to ~200 keV
- one reaction rate may affect a number of isotopic abundances

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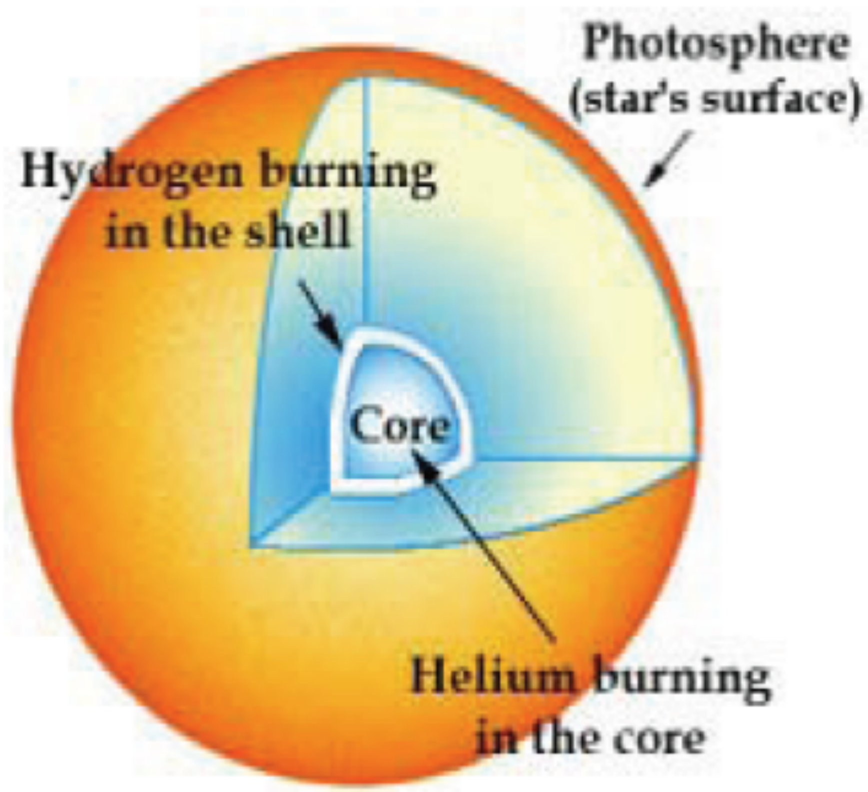

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- **enhanced s-process**
- Rotation mixing leads to higher production of neutron source ^{22}Ne
- enhanced production of weak s isotopes
- if star metal poor, element production up to Ba possible
(Frischknecht U., Hirschi R., Thielemann F.-K., 2012, A&A, 538, L2)

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Uncertainties in *s*-process nucleosynthesis in massive stars determined by Monte Carlo variations

N. Nishimura (西村信哉),[1,2★†] R. Hirschi,[1,3†] T. Rauscher,[4,5†] A. St. J. Murphy[6†] and G. Cescutti[5,7†]

- Simultaneous variation of (n,γ) rates and beta decays
- Rates varied by experimental or theoretical uncertainties
- Extract correlation between reaction rate and final abundance
- If correlation over a certain value, reaction considered “key reaction“

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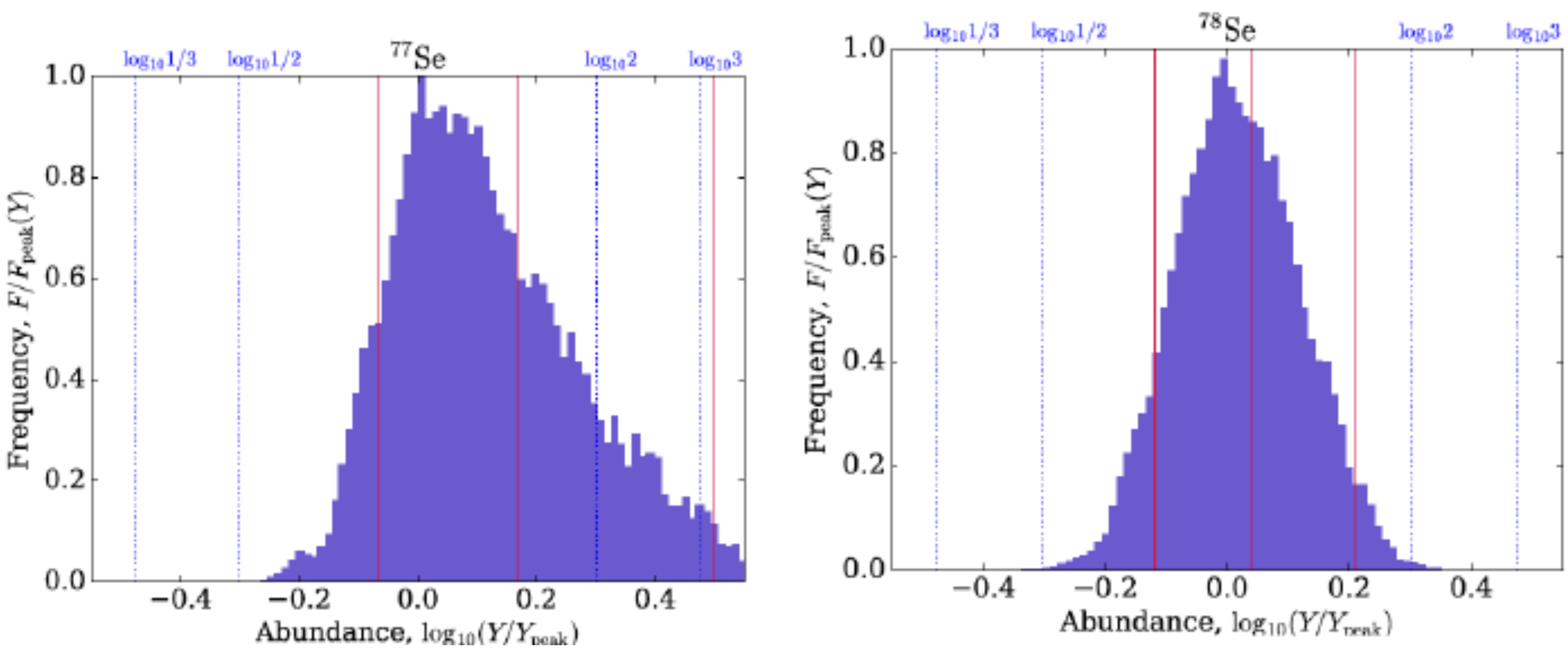

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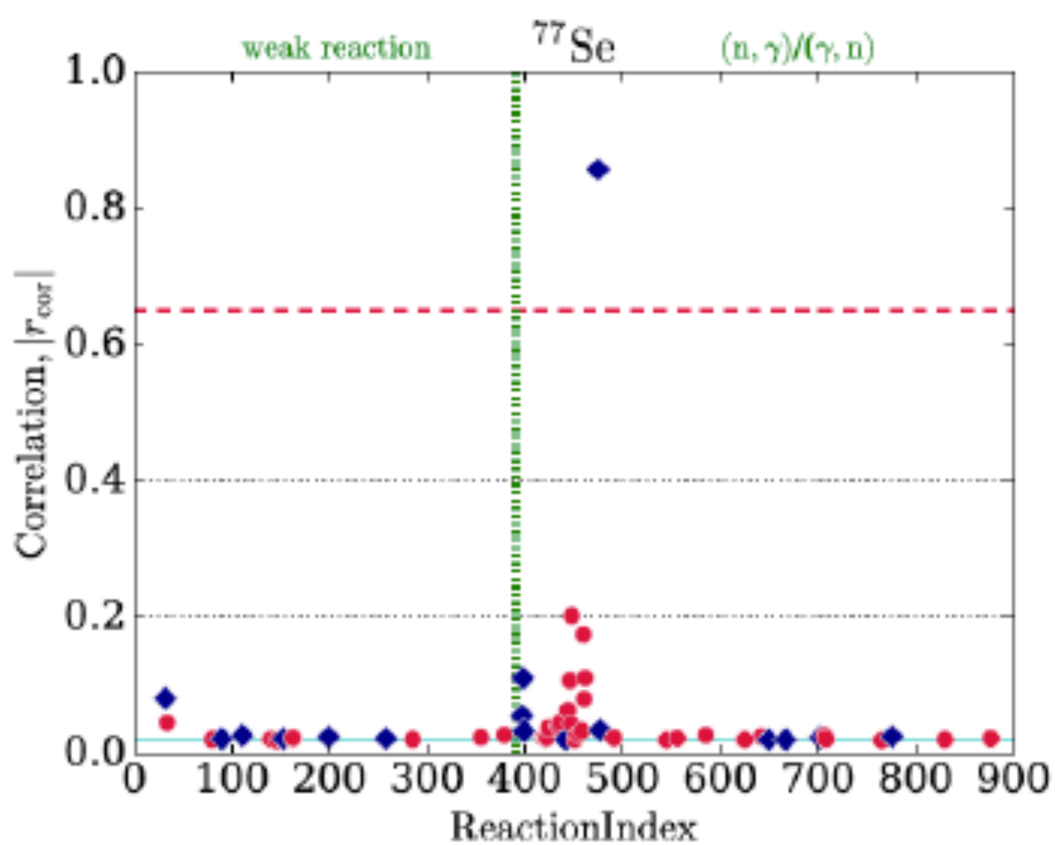

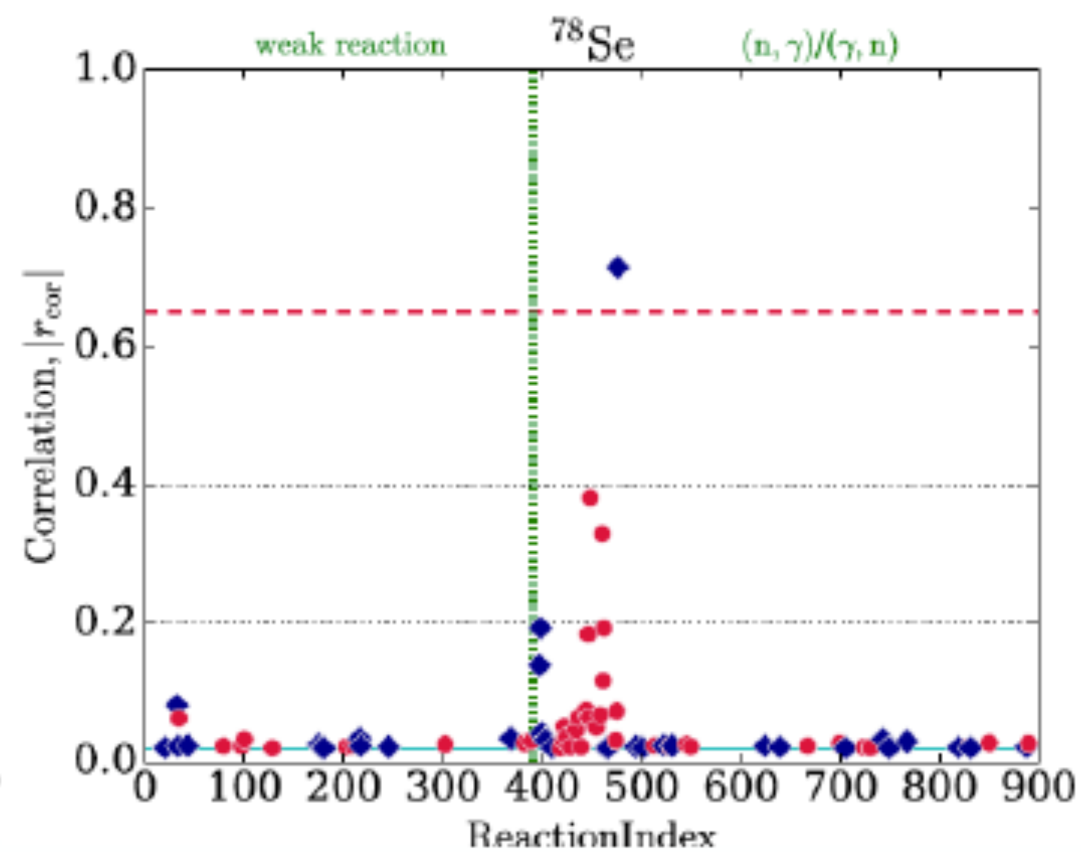

Key reactions in the weak s-process

Nuclide	$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key Rate Level 1	Key Rate Level 2	Key Rate Level 3	X_0 (8, 30 keV)	Weak Rate (8, 30 keV)
^{64}Zn	0.76			^{64}Cu(β^-)^{64}Zn				1.30, 1.36
	-0.46	-0.73			^{64}Cu(e$^-$, ν_e)^{64}Ni			e$^-$ capture
^{67}Zn	-0.67			^{67}Zn(n, γ)^{68}Zn			1.00, 1.00	
^{72}Ge	-0.85			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{73}Ge	-0.84			^{73}Ge(n, γ)^{74}Ge			0.88, 0.81	
^{74}Ge	-0.44	-0.54	-0.67			^{74}Ge(n, γ)^{75}Ge	1.00, 1.00	
^{75}As	-0.50	-0.59	-0.70			^{75}As(n, γ)^{76}As	1.00, 1.00	
^{77}Se	-0.86			^{77}Se(n, γ)^{78}Se			1.00, 1.00	
^{78}Se	-0.71			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
	0.38	0.68			^{68}Zn(n, γ)^{69}Zn		1.00, 1.00	
^{80}Se	-0.76			^{80}Br(β^-)^{80}Kr				1.31, 4.70
	0.27	0.73			^{80}Br(β^+)^{80}Se			1.31, 4.70
	0.16	0.44	0.88			^{80}Br(e$^-$, ν_e)^{80}Se		e$^-$ capture
^{79}Br	-0.64	-0.73			^{79}Br(n, γ)^{80}Br		1.00, 1.00	
^{81}Br	-0.80			^{81}Kr(n, γ)^{82}Kr			1.00, 0.98	
^{83}Kr	-0.76			^{83}Kr(n, γ)^{84}Kr			0.81, 0.74	
^{84}Kr	-0.49	-0.65	-0.76			^{84}Kr(n, γ)^{85}Kr	1.00, 1.00	
^{86}Kr	0.84			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	-0.30	-0.70			^{86}Kr(n, γ)^{87}Kr		1.00, 1.00	
	-0.34	-0.62	-0.90			^{85}Kr(β^-)^{85}Rb		1.30, 1.30
^{87}Rb	-0.56	-0.65	-0.95			^{87}Rb(n, γ)^{88}Rb	1.00, 1.00	

Key reactions in the enhanced weak s-process

Rotation in metal poor stars significantly enhances production of s-process nuclei

Nuclide	$r_{cor,0}$	$r_{cor,1}$	$r_{cor,2}$	Key Rate Level 1	Key Rate Level 2	Key Rate Level 3	X_0 (8, 30 keV)	Weak Rate (8, 30 keV)
^{65}Cu	-0.83			^{65}Cu(n, γ)^{66}Cu			1.00, 1.00	
^{64}Zn	0.72			^{64}Cu(β^-)^{64}Zn				1.30, 1.36
	-0.45	-0.67			^{64}Cu(e$^-$, ν_e)^{64}Ni			e$^-$ capture
	-0.36	-0.52	-0.72			^{64}Zn(n, γ)^{65}Zn	1.00, 1.00	
^{66}Zn	-0.96			^{66}Zn(n, γ)^{67}Zn			1.00, 1.00	
	-0.13	-0.58	-0.67			^{57}Fe(n, γ)^{58}Fe	0.73, 0.59	
^{67}Zn	-0.97			^{67}Zn(n, γ)^{68}Zn			1.00, 1.00	
^{68}Zn	-0.98			^{68}Zn(n, γ)^{69}Zn			1.00, 1.00	
^{69}Ga	-0.92			^{69}Ga(n, γ)^{70}Ga			1.00, 1.00	
^{71}Ga	-0.97			^{71}Ga(n, γ)^{72}Ga			1.00, 1.00	
^{70}Ge	-0.95			^{70}Ge(n, γ)^{71}Ge			1.00, 1.00	
^{72}Ge	-0.94			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{73}Ge	-0.94			^{73}Ge(n, γ)^{74}Ge			0.88, 0.81	
	0.03	0.82			^{64}Ni(n, γ)^{65}Ni		1.00, 1.00	
^{74}Ge	-0.97			^{74}Ge(n, γ)^{75}Ge			1.00, 1.00	
^{75}As	-0.96			^{75}As(n, γ)^{76}As			1.00, 1.00	
^{76}Se	[illegible]			^{76}Se(n, γ)^{77}Se			1.00, 1.00	
^{77}Se	-0.93			^{77}Se(n, γ)^{78}Se			1.00, 1.00	
^{78}Se	-0.97			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
	0.07	0.46	0.70			^{56}Fe(n, γ)^{57}Fe	1.00, 1.00	
^{80}Se	-0.78			^{80}Br(β^-)^{80}Kr				1.31, 4.70
	0.18	0.47	0.89			^{80}Br(e$^-$, ν_e)^{80}Se		e$^-$ capture
^{79}Br	-0.96			^{79}Br(n, γ)^{80}Br			1.00, 1.00	
^{81}Br	-0.86			^{81}Kr(n, γ)^{82}Kr			1.00, 0.98	
^{80}Kr	-0.28	-0.78			^{80}Br(β^+)^{80}Se			
	-0.30	-0.43	-0.67			^{80}Kr(n, γ)^{81}Kr	1.00, 1.00	

Present Data

$^{68}Zn(n,\gamma)$

- One measurement (Garg et al. 1982) at stellar energies (1-350 keV), **12.5%** uncertainty of MACS at kT=25 keV. —> **We could reach 4.4% uncertainty for ^{62}Ni (similar MACS)**

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- Resolved resonance parameters up to 4 keV—> **we can extend resolved resonance region**
- One measurement (Igashira et al. 2010) 15-100 keV —> **we can extend that to 200 keV which covers entire astrophysical energy range**
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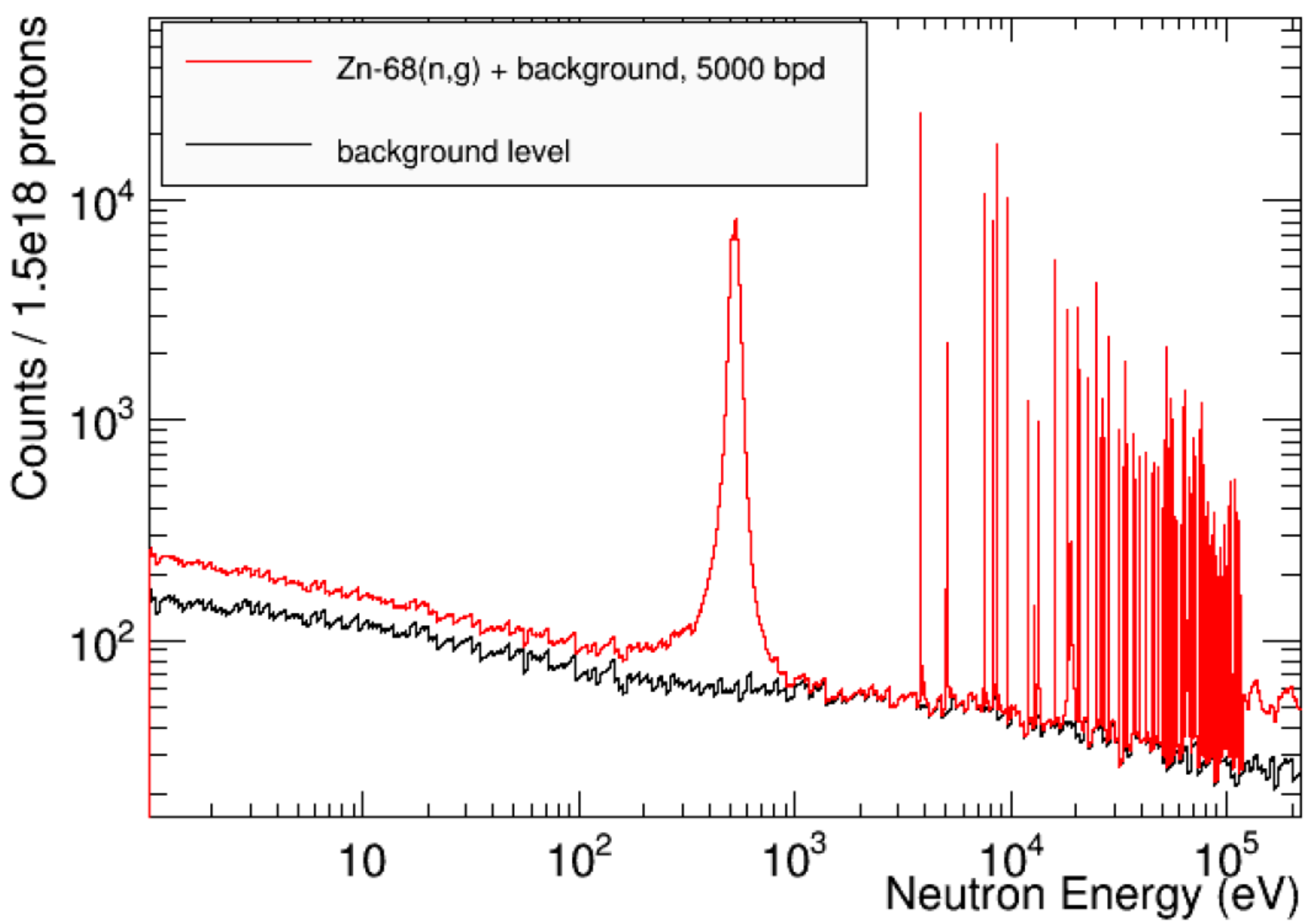
$^{78}Se(n,\gamma)$

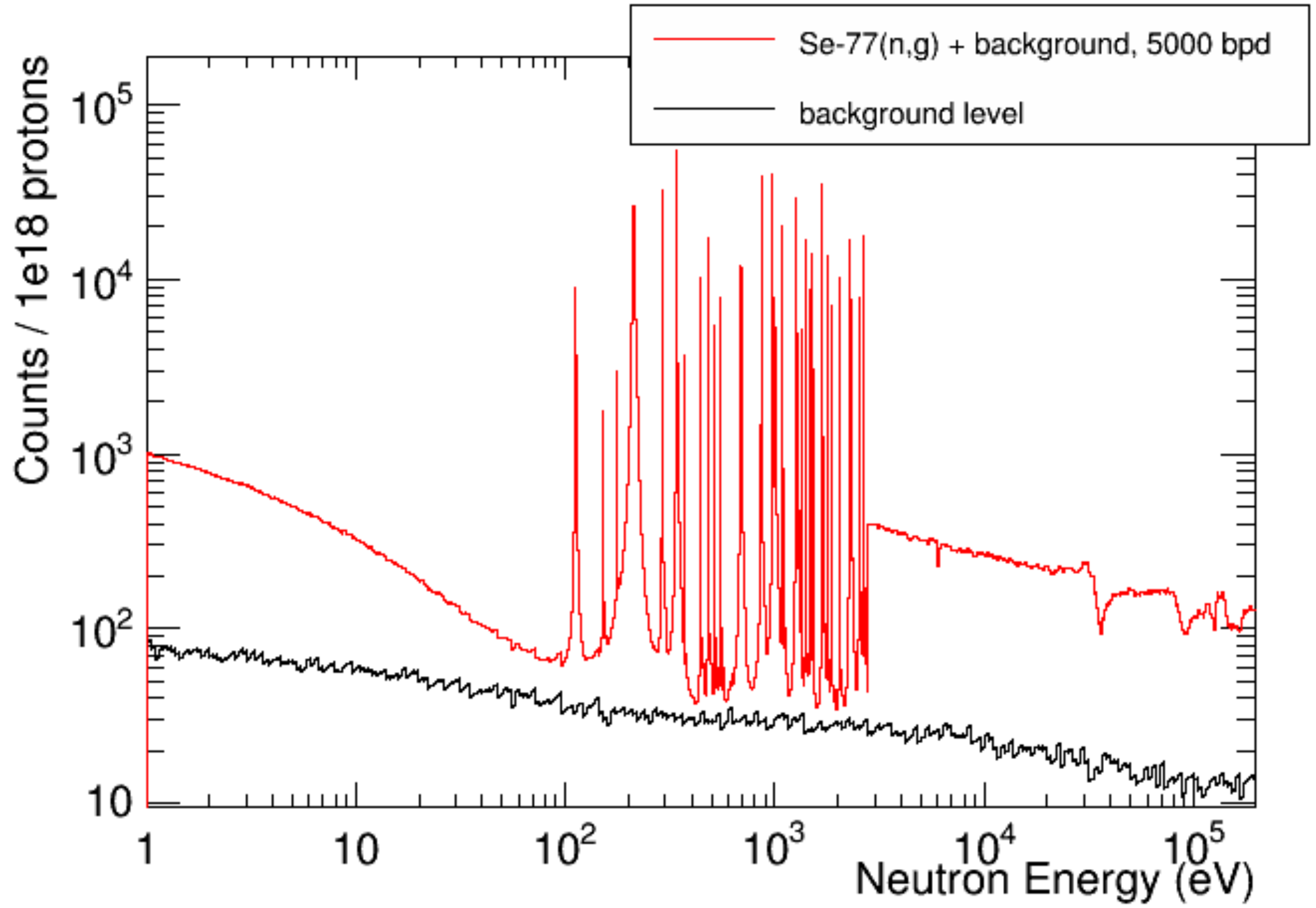
- Resolved resonance parameters up to 7 keV —> **we can extend resolved resonance region**
- Discrepancy (50%) between activation study (Dillmann et al.) and TOF measurement (Kamada et al.)

Beam Time Request

- n_TOF EAR-1 – high neutron energy resolution, high neutron flux
- C_6D_6 Detection system – low neutron sensitivity

Sample	Mass (g)	Purity (%)	Thickness (at/b)	No. of Protons ($\times 10^{18}$)
^{68}Zn	2	98.2	6×10^{-3}	1.5
^{77}Se	1	95.3	2.5×10^{-3}	1.0
^{78}Se	2	98.2	5×10^{-3}	1.5
Au				0.2
Empty Frame				0.5
Neutron filters				0.3
Total				**5.0**





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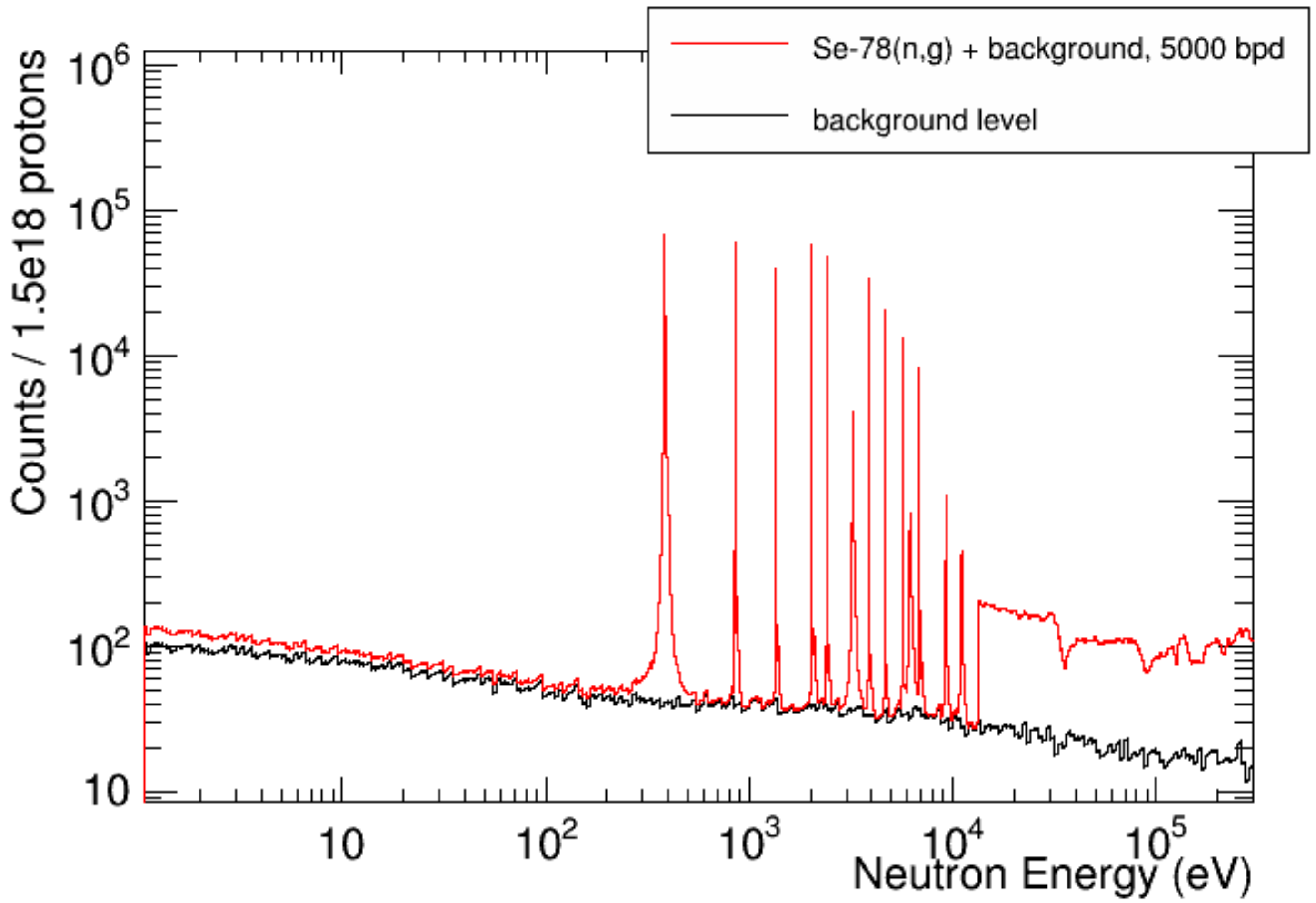
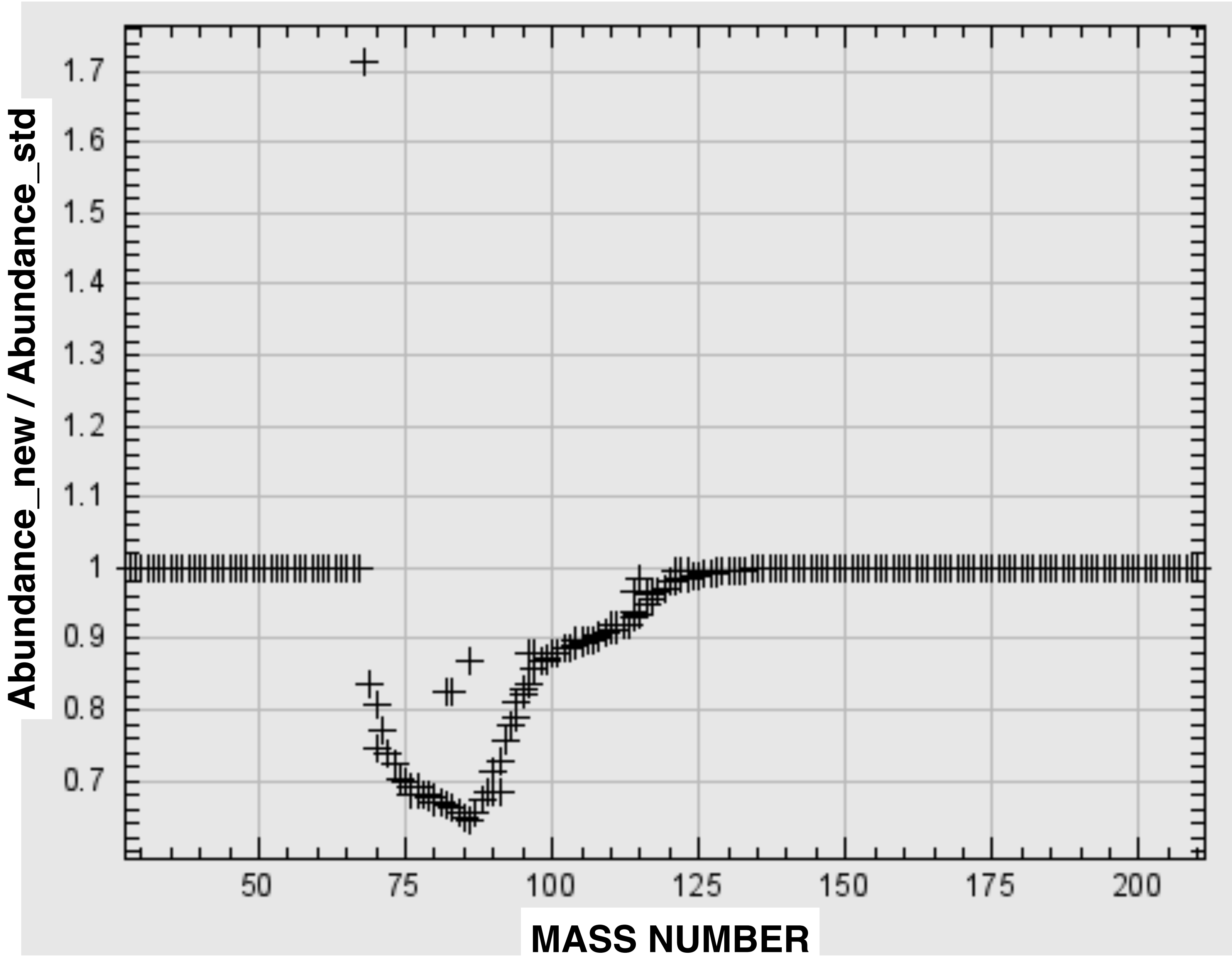


Back up slides

^{68}Zn(n,γ)x0.5: abundance change with cross section change



NETZ online Tool (M. Weigand, Physical Review C 94 (2015) 045810 (open access))
http://exp-astro.physik.uni-frankfurt.de/netz/index.php?model_id=1&itype=Zn&mass=68&rtype=ng&factor=0.5